

SUB-MILLIMETER OBSERVATION OF JUPITER'S STRATOSPHERIC CARBON MONOSULFIDE ($J=7-6$) 19 YEARS AFTER THE COMETARY IMPACT

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ABSTRACT

In Jupiter's stratosphere, gaseous carbon monosulfide (CS) was first discovered in 1994 by millimeter and ultraviolet observations as a product induced by the collision of comet Shoemaker-Levy 9 (SL9). To constrain sulfur chemistry, in 2013, 19 years after the SL9 event, we observed Jupiter's stratospheric CS $J=7-6$ rotational transition at 0.8 mm wavelength by using the Atacama Submillimeter Telescope Experiment (ASTE) 10-m single dish telescope. The CS molecular line was successfully detected with 120 mK intensity in the antenna temperature scale. The obtained CS total mass shows $\sim 90\%$ decrease relative to that observed in 1998. From the line shape analysis, CS is suggested to be present above the $0.2^{+0.4}_{-0.15}$ mbar pressure level, which is comparable to that of determined in 1998.

Keywords: planets and satellites: atmospheres — submillimeter: planetary systems

1. BACKGROUND

Cometary impacts is considered to have affected the stratospheric composition of all four gas giant planets. On Jupiter, the 1994 collision of the fragments of comet Shoemaker-Levy 9 (referred to as the SL9 event) caused the delivery of volatile gases such as CO, HCN, H₂O, S₂, H₂S, OCS, CS₂ and CS in stratosphere (e.g. Noll et al. (1995), Lellouch et al. (1995), Moreno et al. (2003)). Recent sub-millimeter observations have revealed that the upper stratospheric CO molar fraction on Saturn, Uranus and Neptune is larger than that at the lower levels (Lellouch et al. (2005), Hesman et al. (2007), Fletcher et al. (2010), Cavalié et al. (2009), Cavalié et al. (2014)) that indicates the presence of a CO external supply. On Neptune, since the measured CO/H₂O and CO/CO₂ flux ratios are larger than the cometary [CO]/[H₂O] and [CO]/[CO₂] values, the CO was probably formed during a comet impact through shock chemistry rather than a steady influx of Inter-planetary Dust Particle (IDP) and subsequent evaporation Zahnle

(1996). Moreover, observed vertical distribution of the stratospheric CO on Saturn and Uranus match with the cometary impact model, not the IDP model (Cavalié et al. (2010), Cavalié et al. (2014)).

For the understanding of the influence of cometary impact event on the Jovian stratospheric composition, the detailed investigation of the time variation of the mass of the post-SL9 species on Jupiter yield valuable information. We have focused on the most abundant sulfur species (CS) and its chemistry, because S-bearing species may be diagnostic of cometary impacts in other giant planets as well. After the SL9 event, some S-bearing species were newly discovered in Jupiter's stratosphere at various wavelengths ranging from ultraviolet to sub-millimeter. Within a month after the SL9 event, S₂ was observed to be a dominant sulfur reservoir among the species discovered, such as CS₂, OCS, CS and possibly H₂S (Noll et al. (1995), Lellouch et al. (1995)). The abundances of observed S-bearing species have shown different time variations such that while the spectral features of S₂, CS₂, OCS and H₂S had faded within a month (Noll et al. (1995)), CS molecule became a major sulfur reservoir instead. Since the total mass of S₂ observed in 1994 as 10¹⁴ g was comparable with that of CS in 1995, CS was expected to be produced mainly by the conversion of S₂ (Moreno et al. (2003)). To explain the conversion of S₂ into CS, Moses (1996) developed a sulfur chemistry model such that S₂ can produce CS through a reaction with C₂H₃ as follows: S₂ + C₂H₃ + H → 2 CS + 2 H₂. HCS and H₂CS were expected to work as the intermediates to produce CS by the following reactions: HCS + H → CS + H₂, H₂CS + hν → CS + H₂. Frequent millimeter and sub-millimeter observations of CS, HCN and CO have been performed from 1994 to 1998 to monitor their abundance, horizontal and vertical distributions by using the Institut de Radioastronomie Millimétrique (IRAM) 30-m telescope and 15-m James Clerk Maxwell Telescope (JCMT). Since the total mass of CS measured in 1998 as 1.4±0.6×10¹³ g was within the uncertainty of the value measured in 1995, no time variation of CS abundance was found during the monitoring period. The vertical distribution of CS was modeled as a simple two-layer model with a p₀ cut-off pressure level. In 1995, the p₀ value was derived to be 0.15 mbar at a longitude of 44°S where the collision sites were located. Owing to the vertical diffusion of gases, the p₀ pressure level moved downward to approximately 0.2 mbar and 0.3 mbar in 1996 and 1998, respectively. Moreno et al. (2003) expected the p₀ value in 2014 to be 1.0 mbar according to the vertical transportation model.

Besides Jupiter, several attempts have been made to detect S-bearing species on Saturn and Neptune (Fletcher et al. (2012), Iino et al. (2014)). However, negative observation results of SO₂, H₂S and CS on Saturn, and additional SO, OCS and C₃S on Neptune have been reported. The discrepancies of these results with that of Jupiter is interesting since the cometary impacts on both planets have been suggested as the source of external CO in Saturn and Neptune.

A new observation of CS in Jupiter, 19 years after the SL9 event, could yield important information on the long-term evolution of its abundance and hence on the sulfur chemistry in the Jovian atmosphere. Although the conversion process of S₂ into CS occurring just after the impact has been fully explained already (Moses (1996)), the sulfur chemistry related to the destruction of the CS is unknown.

In 2013, we conducted a new observation at submillimeter wavelength, which are typically sensitive to the stratospheric temperature and composition. In this paper, detail of the observation, data analysis and observation results are given in section 2. The sulfur chemistry in Jupiter's stratosphere is discussed in section 3.

2. METHODS

2.1. Observation

Our observation was performed by using the Atacama Sub-millimeter Telescope Experiment (ASTE) 10-m single-dish telescope (Ezawa et al. (2004)), operated by National Astronomical Observatory of Japan (NAOJ), located at an altitude of 4800 m on the Atacama highland, Chile. Observation was performed from 9:36 UT to 11:33 UT, October 1, 2013. The angular diameter of Jupiter was 37.5" whereas the full width half maximum (FWHM) of the ASTE at the 350 GHz band is 22". The observation was conducted during the same period as our Neptune observation (Iino et al. (2014)).

We used a sideband separating mixer receiver CATS345 (Inoue et al. (2008)) that can be tuned from 324 GHz to 372 GHz. For CS, only the J=7–6 rotational transition is observable in the frequency range of CATS345. Separation of V and H polarization is not available during 2013 observation season. For the back-end, a MAC XF type digital spectrometer (Sorai et al. (2000)) was used with 512 MHz bandwidth and 500 kHz spectral resolution mode. Focus was calibrated before the observing run. Similar to the previous observations of Jupiter and Saturn (Moreno et al. (2003), Cavalié et al. (2010)), both equatorial edges of Jupiter were set as ON and OFF positions to achieve the high signal to noise ratio and remove as much as possible the standing waves induced by the observation of a strong and extended continuum source like Jupiter. The integration time for each ON and OFF position was 15 s. For the pointing accuracy correction, cross-scan pointing observation of Jupiter's continuum emission was performed before

and during the observing time. The scanned direction was for azimuth and elevation, and pointing error for both the direction was calculated and calibrated automatically. The measured pointing error during the observation was 1" and 0" for azimuth and elevation, respectively, which are better than the 2"-3" typical pointing error of the ASTE. Owing to the low elevation angle during the observation as 39.5°-44.5°, the measured system temperature value of 532-627 K was higher than the typical value of ASTE of 250 K.

Just after the observation, one of the standard sources of ASTE, IRC10216, was observed to calibrate the receiver. The obtained 6.1 K CS intensity of IRC10216 is consistent within 10% with the previous single-sideband calibrated intensity of Caltech Submillimeter Observatory(CSO)(Wang et al. (1994)) obtained as 5.7 ± 0.4 K in the antenna temperature scale.

2.2. Observation results

Figure 1 shows one observation scan after the subtraction of OFF from ON integration. The vertical and horizontal axes are expressed in the antenna temperature scale in units of Kelvin, and the rest frequency in GHz. To decrease the observed baseline structure, the polynomial fitting method was employed for each observation scans. Second, all of baseline-corrected scans equivalent to 47 min integration time were averaged. The integrated spectrum is shown in Figure 2 in black lines. The lines seen in the ON and in the OFF spectra (in emission and absorption, respectively, in Figure 2) are blue-shifted and redshifted (respectively) because of the planet rapid rotation. The absorption structure is the subtracted emission of the OFF position. The obtained intensities for respective ON and OFF positions are ~ 120 mK in the antenna temperature scale. The root-mean-square (RMS) noise level achieved here is 18.1 mK. Therefore, detection of the CS line was achieved with 6.6σ confidence.

2.3. Radiative transfer analysis of column density and vertical distribution of CS

For the derivation of the CS abundance and vertical distribution, an atmospheric radiative transfer algorithm developed for terrestrial minor species (Ohyama et al. (2012)) was modified and applied to the spectrum. The rest frequency, line intensity and partition function of CS were extracted from the HITRAN 2012 spectroscopic database (Rothman et al. (2013)). The atmospheric structure employed here was the same as the previous observation (Matthews et al. (2002)). The relationship of the pressure broadening coefficient γ with atmospheric pressure p and temperature T is described as follows: $\gamma = \gamma_0 \times (p/p_0) \times (T_0/T)^n \text{ cm}^{-1} \cdot \text{bar}^{-1}$, where p_0 , T_0 and n are 1 bar, 300 K and 0.75, respectively, and γ_0 is pressure broadening coefficient of CS at p_0 and T_0 as $0.125 \text{ cm}^{-1} \cdot \text{bar}^{-1}$. γ_0 value used here was that of used in the previous study of Moreno et al. (2003) (provided by R. Moreno, private communication). For the continuum opacity, the collision induced absorption (CIA) of $\text{H}_2\text{-H}_2$ and $\text{H}_2\text{-He}$ pairs were employed for each atmospheric layers. The values of CIA were obtained from the HITRAN catalogue. For the main beam efficiency value, we assumed the typical value of ASTE as 0.6. The spherical geometry was modeled to take into account the limb effect. 1-D radiative transfer calculations have been performed on each gridpoints of a grid covering the planet, in which the spacing between gridpoints was set to 100 km (i.e. $\sim 1/720$ equatorial radius). The calculated spectra were averaged assuming the symmetric 2-D Gaussian beam pattern. The calculated opacities of the line center for the equatorial limb and disk center are 0.67 and 0.02, respectively. Various two-layer vertical distribution models in which CS is present uniformly above the $p_0 = 0.01\text{-}1.0$ mbar pressure level were attempted to reproduce the obtained spectrum. Only the CS molar fraction was varied as the free parameters, and the CS column density was derived from the profile.

2.4. Results of radiative transfer

From the analysis of the line width, we find that the most probable p_0 value is 0.2 mbar, which is consistent with the one measured in 1998 as $0.3^{+0.2}_{-0.1}$ mbar (Moreno et al. (2003)). 1σ error of p_0 range goes from 0.05 to 0.6 mbar region. Corresponding mole fraction and column density of $p_0=0.2$ mbar model were 1.1×10^{-9} and 3.48×10^{13} molecules cm^{-2} , respectively. The total mass of CS is 1.6×10^{12} g assuming a horizontally uniform CS distribution, and surface area with 71492 km equatorial and 61492 km polar radius (Archinal et al. (2011)).

We have tested the sensitivity of the column density result against the stratospheric temperature. Column densities were calculated for ± 6 and ± 3 K stratospheric temperature models which includes the previously obtained temperature variation from 160 to 166 K (Moreno et al. (2003), Matthews et al. (2002)). Obtained errors were $3.5^{+1.4}_{-0.8} \times 10^{13}$ molecules cm^{-2} and $3.5^{+0.6}_{-0.6} \times 10^{13}$ molecules cm^{-2} for ± 6 and ± 3 K models, respectively. These values are equivalent to $^{+41}_{-22}$ % and $^{+18}_{-17}$ % uncertainties. CS vertical profile for the $p_0 = 0.05, 0.20$ and 0.60 mbar models, ± 6 and ± 3 K stratospheric temperature models are plotted in Figure 3 along with that of CS measured in 1998 (Moreno et al. (2003)).

3. DISCUSSION

In May 1995, 10 months after the SL9 event, the CS column density measured at 44°S at the latitude of comet collision was reported as $0.6\text{--}1.4 \times 10^{15} \text{ cm}^{-2}$ corresponding to a total mass of $2.0 \pm 1.0 \times 10^{13} \text{ g}$ (Moreno et al. (2003)). During the long-term monitoring of CS from 1995 to 1998, its total mass did not show a significant change, and the best fit value throughout the period was reported as $1.8 \pm 0.4 \times 10^{13} \text{ g}$. Thus, our new observation shows that the CS total mass measured in 2013 decreased by up to $\sim 90\%$ with respect to that of in 1998. Due to the low S/N, we have not attempted to constrain the temporal variation of the vertical distribution of CS and thus eddy mixing in Jupiter's stratosphere.

Explaining the decrease of the CS column density is important for the understanding of the sulfur chemistry in the stratosphere of gas giants. Condensation or polymerization processes may contribute to the removal of CS from the gas phase to produce solid or liquid phase, or polymerized CS expressed as $(\text{CS})_n$. Phase change or polymerization of CS could occur in the stratosphere as temperature decreases and number density increases with decreasing altitude. However, the precise evaluation of the phase change is unavailable due to the absence of phase change parameters in the literature. Polymerization is a characteristic phenomenon of S-bearing species. In particular, polymerization of CS on the aerosol surface, which would occur and remove the gas phase CS. The other scenario is that other S-bearing species works as the sulfur reservoir in the deep stratosphere. However, in 1995 and 1996, while some S-bearing species such as H_2CS , NS, SO, H_2S and HNCS were searched already in millimeter waveband, none of them were detected (Moreno et al. (2003)).

From the photochemical perspective, the discovery of CS even in 19 years after the production is interesting because CS is considered to be a chemically unstable molecule due to its short lifetime against the photolysis and high reactivity. Photolysis ($\text{CS} + h\nu \rightarrow \text{C} + \text{S}$) is the rapid destruction process of CS in the gas phase. Therefore, the discovery of a CS molecule on Jupiter suggests the presence of a strong ultraviolet shielding to prevent the CS photolysis or a recycling process for CS. Photodissociation of CS occurs at wavelength $\lambda = 1362, 1401$ and 1542 \AA (Sanzovo et al. (1993)). Since these absorption wavelength is covered with the photodissociation band of major hydrocarbons such as CH_4 , C_2H_4 and C_2H_6 (Gladstone et al. (1996)), CS photodissociation may be prevented efficiently. Even if the photodissociation occurs, dissociated S-atom could react with hydrocarbon radical rapidly as follows: $\text{S} + \text{CH}_3 \rightarrow \text{H}_2\text{CS} + \text{H}$, $\text{S} + \text{CH}_2 \rightarrow \text{HCS} + \text{H}$. Produced H_2CS and HCS probably photodissociate to produce CS.

In the case of Neptune, a previous large cometary impact is suggested by the larger external flux of CO than that of water vapor (Lellouch et al. (2005), Hesman et al. (2007)). The absence of CS (and other S-bearing molecules), as found with ASTE (Iino et al. (2014)), could contradict the comet impact hypothesis. However, a detailed sulfur chemistry model should be developed for the further assessment whether the absence of CS is compatible with a comet impact scenario on Neptune (and also on Saturn). Such a model would be helpful in understanding the temporal evolution of the CS mass in Jupiter's stratosphere. The new development of the detailed sulfur chemistry model includes the precise estimation of ultraviolet shielding and other photochemical processes is helpful. Once the sulfur chemistry on Jupiter is revealed, the result will be a good reference not only to Neptune but also to Saturn where the previous cometary impacts are suggested.

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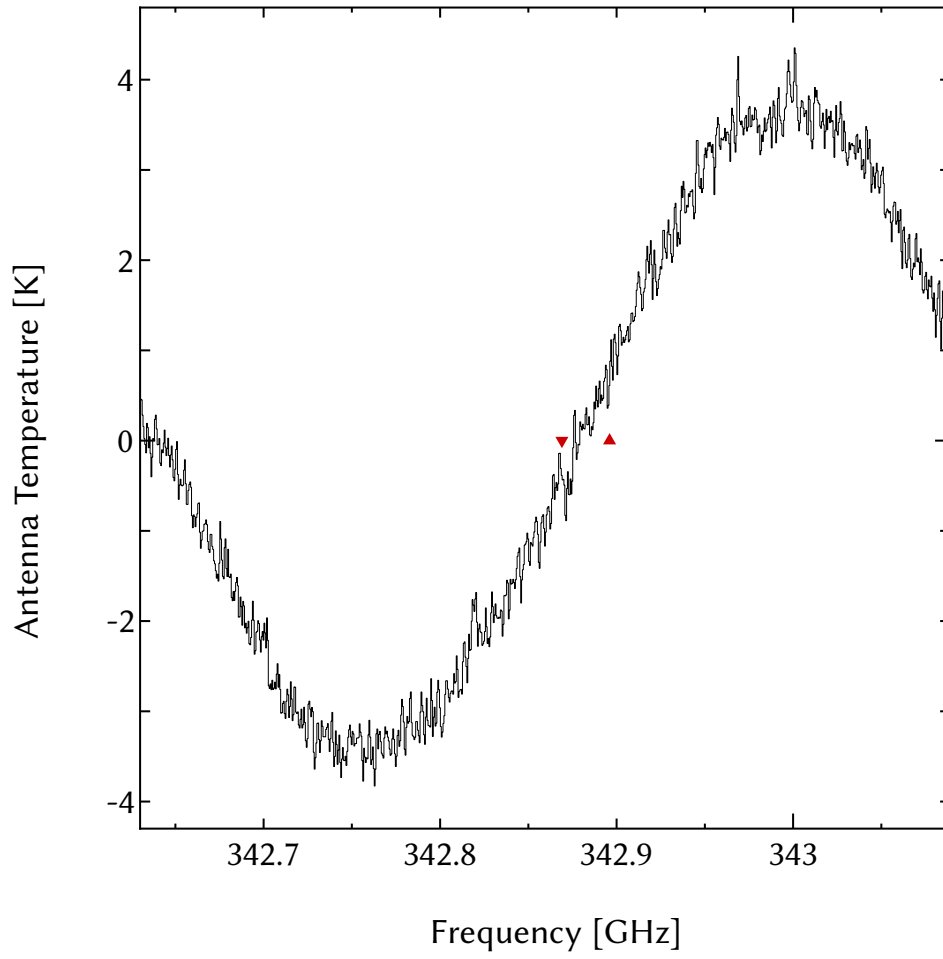


Figure 1. A raw spectrum for 15 seconds integration time. Each spectrum were averaged after the correction of the baseline structure by the polynomial function. Red triangles indicate where the Doppler-shifted CS lines are expected.

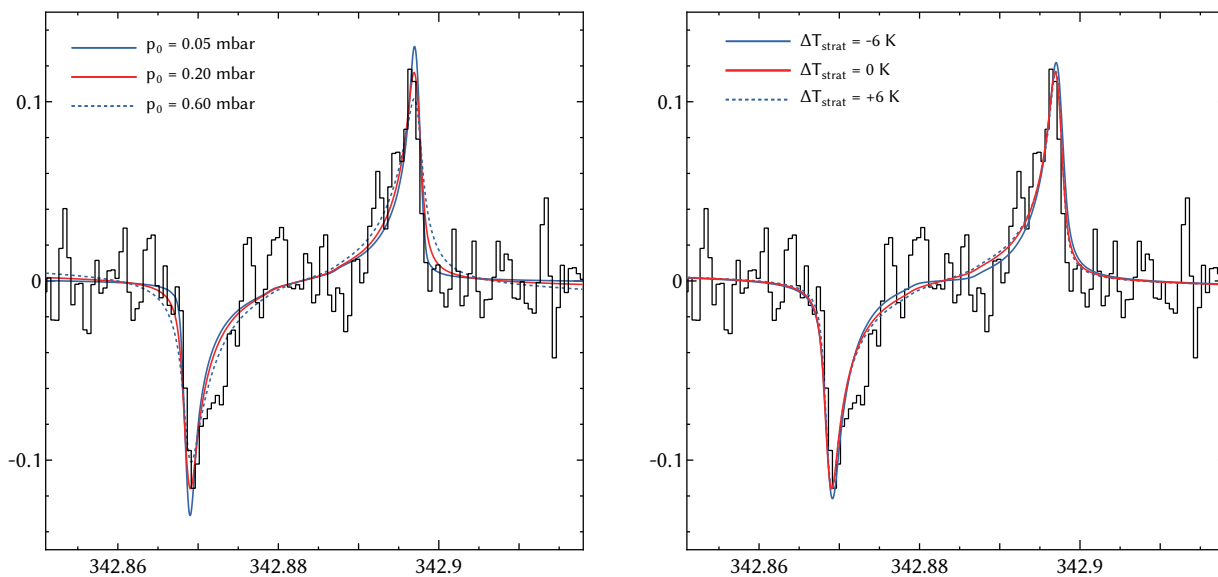


Figure 2. left panel: Observed (solid black line) and modeled spectra for $p_0 = 0.05$ (thin blue), 0.20 (thick red) and 0.60 (dotted blue) mbar vertical distribution. right panel: Comparison of the best-fit spectra for +6 K (dotted blue) and -6 K (thin blue) stratospheric temperature (ΔT_{strat}). p_0 is fixed to 0.2 mbar.

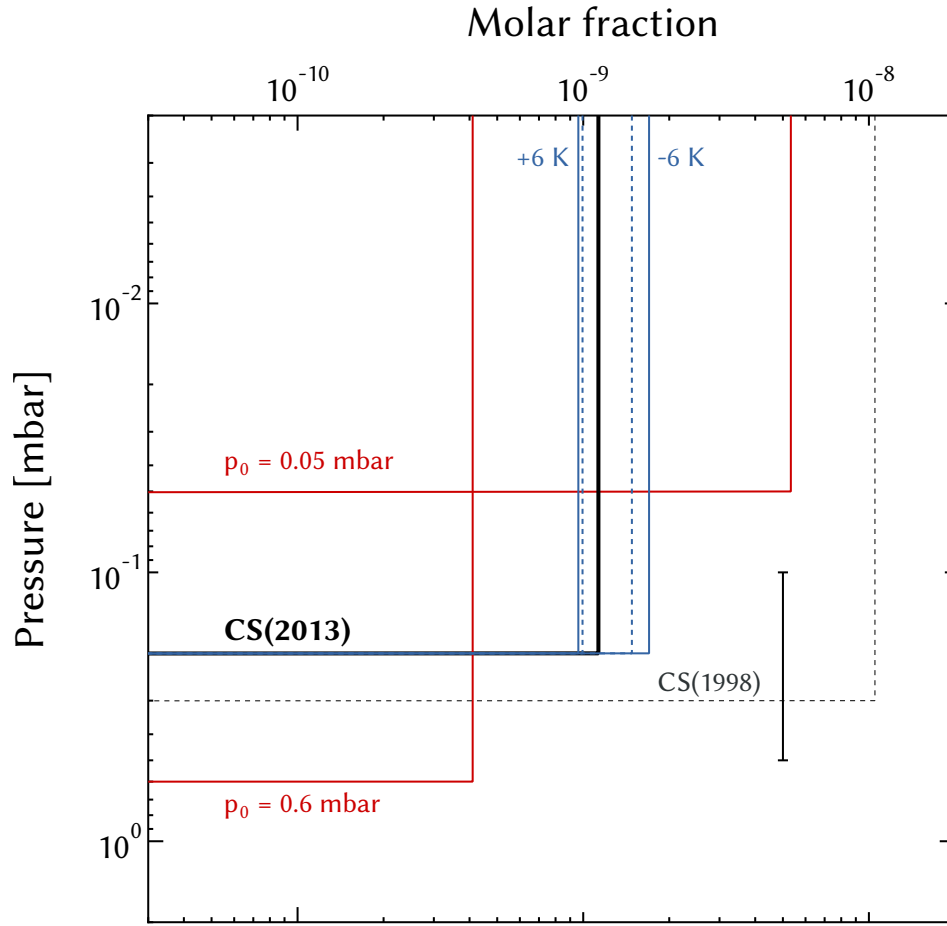


Figure 3. Thick black line shows the best fit CS vertical distribution model as $p_0 = 0.20$ mbar and 1.1×10^{-9} molar fraction. The p_0 value measured in 1998 is consistent with this work. Respective blue solid and dashed lines are for the ± 6 and ± 3 K stratospheric temperature models. CS profile measured in 1998 is plotted in thin black dashed line with its errors on p_0 .

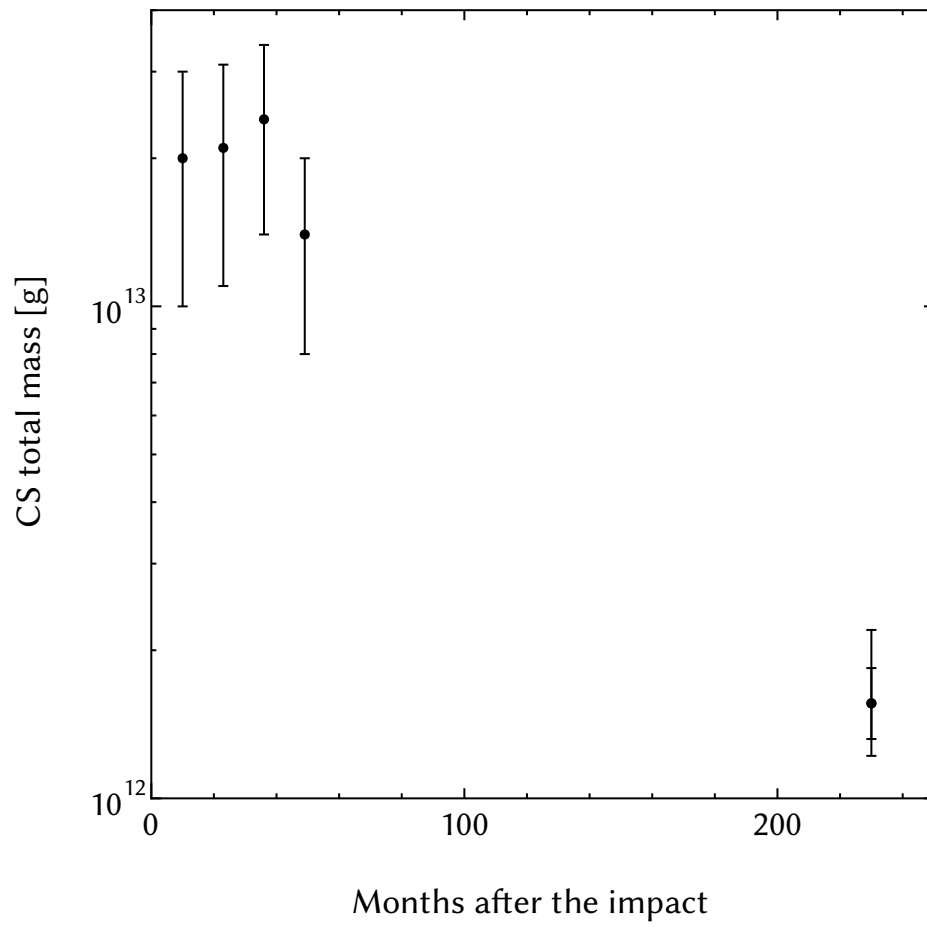


Figure 4. The time variation of CS total mass from 1995 to 2013 plotted in logarithm with respect to the months after the SL9 impact. Two error bars in this work corresponds to ± 3 and ± 6 K stratospheric temperature. CS total mass measured in 2013 shows $\sim 90\%$ decrease in comparison with from 10 to 49 months period.